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Artificial Aging of Zirconium Dioxide: An Evaluation of Current Knowledge and Clinical Relevance

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Abstract Due to its superior mechanical properties, yttrium-stabilized tetragonal zirconia polycrystal is considered as one of the most promising materials to manufacture prosthetic frameworks, monolithic crowns and abutments for implants in dentistry. When stabilized in the tetragonal phase, the structure of zirconia can respond to external stress by increasing its toughness and resistance. Unfortunately, when subjected to humid environment, zirconia may undergo considerable degradation characterized by increased surface roughness, grain growth and propagation of microcracks that could be detrimental for its mechanical properties. This phenomenon, also known as low-temperature degradation (LTD), when not minimized, may represent a setback for the longevity of zirconia especially used for biomedical applications. LTD is studied in *in vitro* or *in vivo* settings employing different strategies. Present clinical studies however, with their shortcomings, do not signify high incidence of failures of zirconia for dental applications. The LTD of zirconia is currently being criticized based on laboratory testing which may be suboptimal. This review will highlight the existing knowledge on the artificial aging methods studying LTD in zirconia and their relevance considering clinical performance of zirconia prostheses.

Keywords Aging • Low temperature degradation • Zirconia • Y-TZP

Introduction

With the introduction of CAD/CAM technologies, many dental reconstructions, which could be rehabilitated with metal-ceramic, can currently be restored with ceramic materials [1,2]. Among all other ceramic alternatives, Yttrium-stabilized tetragonal zirconia polycrystal (hereon: zirconia) has more potential for diverse dental applications. Due to its biocompatibility, superior mechanical properties, chemical stability and laboratory versatility, zirconia has been indicated to manufacture monolithic crowns, frameworks of fixed dental prostheses (FDPs), root posts, implant abutments and implants [3-5].

Zirconia as a biomaterial

Zirconia is a white oxide that displays a singular allotropic effect. With the same composition, it can present three different crystal structures transforming as a function of temperature, namely monoclinic (from room temperature up to 1170°C), tetragonal (1170-2370°C) and cubic phase (>2370°C) [6]. Among all three phases the monoclinic phase is mechanically the weakest and predominates pure zirconia. It is essential to maintain zirconia in the tetragonal and/or cubic phase at room temperature in order to benefit from its mechanical properties [7]. For this purpose, typically oxides (CaO, MgO) and rare earths (CeO₂, Y₂O₃) are added to zirconia, stabilizing this material fully or partially at these phases [8]. According to the ISO 13356, yttrium oxide (Y₂O₃) is the most suitable stabilizer for medical use [9] where usually about 3 to 6 mol% of Y₂O₃ is capable of stabilizing zirconia in the tetragonal phase [10].

Zirconia is considered as a structural material due to the fact that when subjected to stress, it can change its microstructure, improving its mechanical performance [8]. In general, ceramic materials do not exhibit deformation capability and when submitted to stresses, fractures may occur as a result of crack propagation originating from internal or external defects. However, when a crack propagates into zirconia structure tetragonal metastable crystals close to the crack tip transform spontaneously into the monoclinic phase ($t \rightarrow m$).

phase transformation) resulting in a volumetric expansion of about 3 to 5% [11]. This volume increase induces compressive stresses that oppose the growth and propagation of the crack, resulting in a mechanism known as "transformation toughening" [12,13]. During this process, the crystalline structure of the material changes. Hence, without mass transfer, simultaneous movement of the atoms results in modification of the macroscopic shape of the processed areas that considerably improves the strength of zirconia [13].

Since the energy available for crack propagation is in part dissipated in the damaged area shaped by the monoclinic zirconia, transformation toughening occurs [14]. However, when the increase in volume exceeds the elastic limit of zirconia, it can promote the crack propagation, inducing new microcracks and even catastrophic fracture of the structure [8]. This mechanism could be influenced by several factors that act in an isolated form or associated, such as shape, size and location of grains, presence of defects and/or oxygen vacancies in the structure, type and amount of stabilizing oxides, manufacturing methods, applied stresses and temperature variation [3].

More recently, with the introduction of CAD/CAM technologies and aesthetic requirements, zirconia was introduced in dentistry. Commercial blocks, obtained through isostatic compaction of zirconia nanoparticles (20-30 nm) could be machined by CAD/CAM milling technologies and sintered at high temperature furnaces [3]. The microstructure of zirconia at this stage is mainly composed of tetragonal grains.

Low-temperature degradation

Zirconia is a chemically inert material with low toxicity [3,15]. Owing to its high flexural, fracture strength, hardness, modulus of elasticity and wear resistance [4], in the late 80s, zirconia has been used in medicine to manufacture orthopedic femoral head prostheses [14-16]. Unfortunately, between 2000 and 2002, a large number of failures were observed in a short period of time, generating a major public health concern. These

failures have drawn attention of the scientific community and consequently, efforts have been made in order to search for the origin of such premature failures of orthopedic prostheses experienced.

Several researchers observed that zirconia is destabilized in the presence of water or water vapour and the moisture favoured the $t \rightarrow m$, significantly increasing the monoclinic content and ultimately, the surface roughness of the material [16,17]. The phenomenon responsible for such premature failures was then attributed to hydrothermal degradation or low-temperature degradation (LTD), known as *aging* of zirconia in the medical field [17,18]. Subsequent studies also supported the hypothesis that when zirconia is exposed to a humid environment, aging can take place at varying degrees [14,15,18].

LTD is a structural degradation phenomenon that starts on the zirconia surface and continues when it is in contact with water or water vapour at moderate temperatures ranging between 150 and 400°C [19]. The presence of moisture interferes with the metastability of its microstructure, and makes the material susceptible to aging [6,15,18,20]. Usually, the surface transformation is slow, spontaneous and progressive. LTD starts with the stress corrosion mechanism where the diffusion of water into the zirconia grains occurs through filling the oxygen vacancies and causes stresses in the crystalline network, which then disorganizes the structure of the material [6]. This scenario is characterized by nucleation and growth of the transformed grains, successive grain pull-out and micro or macrocracks formation, also known as subcritical crack growth (SCG) phenomenon [17]. As the grain size increases with the increase in monoclinic phase, the result is the formation of a path created by cracks through which water penetrates, further increasing the susceptibility to LTD [6].

Several theories have been proposed in order to elucidate the LTD [21-23]. Early theories postulated that LTD occurs due to chemisorption of water molecules [21,24] that could break the Y-O bonds, which is also known as SCG. The classic model proposed by Guo [25] described the LTD phenomena in sequential phases: a) water chemical adsorption on the grain surface; b) water reaction with oxygen, forming hydroxyl groups; c) penetration of the hydroxyl groups into the mass by diffusion around the grain; d) formation of proton defects

by filling the oxygen vacancies with hydroxyl ions; and e) $t \rightarrow m$ transformation reducing the concentration of oxygen vacancies. On the other hand, the most widely accepted theory suggests that the increase in internal stresses associated with the penetration of water triggers the $t \rightarrow m$ phase transformation, yielding to LTD [26].

In fact, aging of zirconia is the result of the influence of multiple factors. The $t \rightarrow m$ transformation is strongly induced by the presence of water or water vapor [25], material susceptibility [20], shape, size and grain location and stabilizer content [27]. In this regard, after aging, depending on the composition, zirconia shows variability in the mechanical behaviour due to different levels of $t \rightarrow m$ transformation zones [28,29]. The reduction in the resistance of zirconia appears to be closely linked to a more pronounced depth in the transformation zones [30,31]. However, the shape, size and location of the grains appear to have the highest impact on phase transformation in that larger grains are more easily transformed than smaller ones [10,22,27]. Parameters such as aging duration, temperature and pressure also determine the intensity of transformation. Aging duration longer than 20 h, pressure of 2 bar and temperature of 134°C seems to be the ideal parameters in order to promote LTD in zirconia specimens [20,23]. Experimental studies also demonstrated grain growth with the increase in temperature [3,32] and that the resulting degradation is dependent on the duration of exposure to the heat [33]. However, recently $t \rightarrow m$ phase transformation was also reported even at room temperatures [34].

Methods for LTD simulation

To date there is little *in vivo* data on the effect of LTD on zirconia. In 1993, Shimizu et al. evaluated aging of zirconia specimens that were placed in the subcutaneous tissue of rabbits, stored in saline solution at 37, 50 and 95°C for 36 months or by aging them in autoclave at 121°C for 960 h [35]. The results indicated similar levels of aging in *in vivo* and *in vitro* conditions. Thus, the authors suggested that *in vitro* studies could be used to screen hydrothermal degradation of zirconia. Recently, in an *in vivo* model, LTD was studied after placing

zirconia discs with two different grain sizes (0.32 and 0.44 μm) in removable mandibular dentures [36]. After 6, 12 and 24 months exposure to the oral cavity, discs were removed from the prostheses and the surfaces were analyzed using X-ray Diffraction (XRD) and Field Emission Gun Scanning Electron Microscope (FEG-SEM). The results showed that regardless of the grain size, zirconia specimens were vulnerable to $t \rightarrow m$ phase transformation due to chemical changes in the aggressive oral environment [36].

In a series of classical *in vitro* studies, Chevalier et al. evaluated the LTD of zirconia in an autoclave at 134°C for 1 h, representing an equivalent to 3 to 4 years of *in vivo* aging [14,23,37]. On the other hand, International Organization of Standardization (ISO 13356:2015) recommends employing autoclave aging at 134°C under 0.2 MPa pressure for 5 h as an accelerated aging protocol for zirconia [9]. As an alternative to autoclave aging, other laboratory tests have been also used to predict and to elucidate the LTD in zirconia such as thermocycling [28,30], mechanical cycling [30], storage in water [37], saliva [31], saline solution [38,39] and acetic acid [39,40].

For the accelerated aging protocol in autoclave, the temperature employed in most studies is 134°C [9,23,28,29,32,41,42] which is also the recommendation of ISO 13356:2015 [9]. However, the duration of exposure of the specimens vary between 1 h to 960 h [32,41,42] where $t \rightarrow m$ phase transformation is directly proportional to the duration of aging [31,32,42]. Unfortunately, the lack of standardization for the LTD method considering duration, temperature, storage in various chemicals makes it difficult to compare LTD phenomenon and suggest strategies to minimize its development [20].

Clinical relevancy

The validity of the accelerated aging protocols and their relevance to the longevity of the zirconia reconstructions remains a question in clinical dentistry [6,20]. Since accelerated aging of zirconia is investigated at higher temperatures than the human body, the testing environment could not be considered

representative for the oral environment, and that the extrapolation of *in vitro* findings should be made with caution [20].

Although clinical follow-up studies of anterior FDPs with zirconia frameworks showed a success rate of 88.8% up to 7 years [43], there is still concern on the possible consequences of LTD in zirconia materials used for dental applications. Especially abutments, FDP frameworks without veneering ceramic or monolithic crowns are directly exposed to the oral environment [44]. Moreover, it has to be noted that already during manufacturing, as a result of CAD/CAM milling along with clinical and laboratory procedures, abutments crowns or FDPs made of zirconia are subjected to damage. Such damage undermines the initial favourable mechanical properties of zirconia [4] that can eventually compromise the longevity of such prostheses especially when they are in contact with the oral environment [37,45].

Zirconia ceramics available for clinical use present dissimilarities but the hydrothermal transformation mechanism could in fact be controlled or minimized during industrial, laboratory and clinical processing. During industrial processing, zirconia ceramic blocks could be produced with controlled density to prevent the destabilization of the tetragonal zirconia microstructure. In addition, alumina traces (Al_2O_3) [38,46], silica and/or ceria (CeO_2) [39] could be added to the composition to improve the resistance of zirconia against LTD. In particular, ceria as an oxide demonstrates favourable stabilization effect as it has concentration of about 12 mol% and makes zirconia non-transformable [47,48].

LTD could also be avoided during laboratory processing by ceramic infiltration and thermal control. In order to shield the surface of zirconia and prevent its contact with humidity, the use of ceramic infiltration with glass ceramic having thermal expansion coefficient similar to that of zirconia could be recommended [49,50]. As for the temperature control, zirconia is typically sintered at temperatures between 1400°C and 1450°C [14]. Temperatures exceeding 1550°C cause grain growth of up to 0.75 μm that is above the recommendations of ISO 13356:2015 (0.6 μm) [17]. The resulting grain growth increases the monoclinic content of zirconia and

thereby susceptibility to LTD [32,33]. Thus, it is essential to sinter zirconia at temperatures low enough in order to avoid larger grain formation but high enough to generate dense structures ensuring cohesion between the zirconia grains. Lower density also facilitates the penetration of water to the bulk of the material, resulting in formation of pores and crack surfaces, greatly increasing LTD. [24].

Clinical strategies involve factors that can be controlled by the dental professional such as the establishment of an appropriate tooth preparation with sufficient depth, rounded interior angles and cervical finish lines. Careful tooth preparation allows for more accurate image processing and CAD/CAM milling, and ensures fewer adjustments on the zirconia surface during clinical try-in [51]. Likewise, every time adjustments are made on the zirconia surface, the damage caused by the burs or disks can deteriorate the surface integrity of zirconia [52]. Superficial roughness created on the material can then introduce defects and increase the susceptibility to $t \rightarrow m$ phase transformation [20]. Thus, repeated slow heating and cooling of the zirconia reconstruction after adjustments and veneering could dissipate the stresses created by burs or disks.

Concluding remarks

Current knowledge, implications and consequences of low-temperature degradation effect on zirconia are mainly based on accelerated aging studies. Clinical follow-up studies should elucidate the *in vivo* consequences of this phenomenon, providing that current studies either lack the power or comprise many confounding factors. At this stage, it is essential that the dental professionals should perform laboratory and clinical procedures meticulously considering factors highlighted in this review in order to minimize the aging process, maintaining mechanical properties and increasing the longevity of zirconia prosthesis.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
- Of major importance

1. Larsson C, Wennerberg A. The clinical success of zirconia-based crowns: a systematic review. *Int J Prosthodont*. 2014;27(1):33-43.
2. Ferrari M, Vichi A, Zarone F. Zirconia abutments and restorations: From laboratory to clinical investigations. *Dent Mater*. 2015;31(3):e63-e76.
3. Uo M, Sjögren G, Sundh A, et al. Cytotoxicity and bonding property of dental ceramics. *Dent Mater*. 2003;19(6):487-92.
4. Denry I, Kelly JR. State of the art of zirconia for dental applications. *Dent Mater*. 2008;24(3):299-307.
5. Vagkopoulou T, Koutayas SO, Koidis P, et al. Zirconia in Dentistry: Part 1. Discovering the nature of an upcoming bioceramic. *Eur J Esthet Dent*. 2009;4(2):130-51.
6. *Lughi V, Sergo V. Low temperature degradation – aging – of zirconia: A critical review of the relevant aspects in dentistry. *Dent Mater*. 2010;26(8):807-20. **This review article focuses on the effects of LTD on zirconia and the main implications for dental applications.**
7. Guazzato M, Albakry M, Ringer SP, et al. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics. *Dent Mater*. 2004;20(5):449-56.
8. Kelly JR, Denry I. Stabilized zirconia as a structural ceramic: An overview. *Dent Mater*. 2008;24(3):289-98.
9. International Standards Organization: Implants for surgery – Ceramic materials based on yttria-stabilized tetragonal zirconia (Y-TZP). No:13356:2008 – revised No:13356:2015.
10. Kumar BVM, Kim WS, Hong S, et al. Effect of grain size on wear behavior in Y-TZP ceramics. *Mater Sci Eng A*. 2010;527(3):474-9.

11. Hannink RHJ, Kelly PM, Muddle BC. Transformation toughening in zirconia-containing ceramics. *J Am Ceram Soc.* 2000;83(3):461-87.
12. Garvie RC, Hannonk RH, Pascoe RT. Ceramic steel? *Nature.* 1975;258:703-4.
13. Kelly PM, Francis Rose LR. The martensitic transformation in ceramics-its role in transformation toughening. *Prog Mater Sci.* 2002;47(5):463-557.
14. Chevalier J, Deville S, Münch E, et al. Critical effect of cubic phase on aging in 3mol% yttria-stabilized zirconia ceramics for hip replacement prosthesis. *Biomaterials.* 2004;25(24):5539-45.
15. Cales B, Stefani Y, Lilley E. Long-term in vivo and in vitro aging of a zirconia ceramic used in orthopaedy *J Biomed Mater Res.* 1994;28(5):619-24.
16. Piconi C, Burger W, Richter HG, et al. Y-TPZ for artificial joint replacements. *Biomaterials* 1998;19(16):1489-94.
17. Chevalier J. What future for zirconia as a biomaterial? *Biomaterials.* 2006;27(4):535-43.
18. Chevalier J, Gremillard L, Virkar AV, et al. The tetragonal-monoclinic transformation in zirconia: lessons learned and future trends. *J Am Ceram Soc.* 2009;92(9):1901-20.
19. Kobayashi K, Kuwajima H, Masaki T. Phase change and mechanical properties of $\text{ZrO}_2\text{-Y}_2\text{O}_3$ solid electrolyte after aging. *Sol Stat Ion.* 1981;3/4:489-95.
20. **Pereira GK, Venturini AB, Silvestri T, et al. Low-temperature degradation of Y-TZP ceramics: a systematic review and meta-analysis. *J Mech Behav Biomed.* 2016;55:151-63. **This is a meta-analysis on low-temperature degradation of zirconia in autoclave. The paper concludes that aging parameters such as duration of aging, pressure and temperature affect mechanical properties and in particular the flexural strength.**
21. Lange FF, Dunlop GL, Davis BI. Degradation during aging of transformation-toughened $\text{ZrO}_2\text{-Y}_2\text{O}_3$ materials at 250°C. *J Am Ceram Soc.* 1986;69(3):237-40.

22. Sato T, Shimada M. Transformation of yttria-doped tetragonal ZrO₂ polycrystals by annealing in water. *J Am Ceram Soc.* 1986;68(6):356-9.
23. **Chevalier L, Cales B, Drouet JM. Low temperature aging of Y-TPZ ceramics. *J Am Ceram Soc.* 1999;82(8):2150-4. **This classical article presents the aging protocol in autoclave at 134 °C for 1 h and suggest this protocol equivalent to 3-4 years of *in vivo* aging.**
24. Yoshimura M, Noma T, Kawabata K, et al. Role of H₂O on the degradation process of Y-TZP. *J Mater Sci Lett.* 1987;6(4):465-7.
25. Guo X. On the degradation of zirconia ceramics during low-temperature annealing in water or water vapor. *J Phy Chem Solids.* 1999;60(4):539-46.
26. Schubert H, Frey F. Stability of Y-TZP during hydrothermal treatment: neutron experiments and stability considerations. *J Eur Ceram Soc.* 2005;25(9):1597-602.
27. Luthardt RG, Holzhüter M, Sandkuhl O, et al. Reliability and properties of ground Y-TZP zirconia ceramics. *J Dent Res.* 2002;81(7):487-91.
28. Flinn BD, deGroot DA, Mancl LA, et al. Accelerated aging characteristics of three yttria-stabilized tetragonal zirconia polycrystalline dental materials. *J Prosthet Dent.* 2012;108(4):223-30.
29. Perdigão J, Pinto AM, Monteiro RC, et al. Degradation of dental ZrO₂-based materials after hydrothermal fatigue. Part I: XRD, XRF, and FESEM analyses. *Dent Mater J.* 2012;31(2):256-65.
30. Borchers L, Stiesch M, Bach FW, et al. Influence of hydrothermal and mechanical conditions on the strength of zirconia. *Acta Biomater.* 2010;6(12):4547-52.
31. Alghazzawi TF, Lemons J, Lui PR, et al. Influence of low-temperature environmental exposure on the mechanical properties and structural stability of dental zirconia. *J Prosthodont.* 2012;21(5):363-9.
32. Denry IL, Peacock JJ, Holloway JA. Effect of heat treatment after accelerated aging on phase transformation in 3Y-TZP. *J Biomed Mater Res B Appl Biomater.* 2010;93(1):236-43.

33. Cattani-Lorente M, Durual S, Amez-Droz M, et al. Hydrothermal degradation of a 3Y-TZP translucent dental ceramic: A comparison of numerical predictions with experimental data after 2 years of aging. *Dent Mater*. 2016;32(3):394-402.
34. Keuper M, Berthold C, Nickel KG. Long-time aging in 3 mol.% yttria-stabilized tetragonal zirconia polycrystals at human body temperature. *Acta Biomater*. 2014;10(2):951-9.
35. *Shimizu K, Oka M, Kumar P, et al. Time-dependent changes in the mechanical properties of zirconia ceramic. *J Biomed Mat Res*. 1993;27(6):729-34. ***This is the first study on LTD effect on zirconia in animals.**
36. *Kosmac T, Jevnikar P, Kocjan A. In vivo ageing of dental zirconia ceramics: 24-months results. *Dent Mater*. 2011;27S:e60-1. ***This is the first *in vivo* study on LTD of zirconia.**
37. Deville S, Chevalier J, Gremillard L. Influence of surface finish and residual stresses on the ageing sensitivity of biomedical grade zirconia. *Biomater*. 2006;27(10):2186-92.
38. Papanagiotou HP, Morgano SM, Giordano RA, et al. In vitro evaluation of low-temperature aging effects and finishing procedures on the flexural strength and structural stability of Y-TZP dental ceramics. *J Prosthet Dent*. 2006;96(3):154-64.
39. Ban S, Sato H, Suehiro Y, et al. Biaxial flexure strength and low temperature degradation of Ce-TZP/ Al_2O_3 nanocomposite and Y-TZP as dental restoratives. *J Biomed Mater Res B Appl Biomater* 2008;87(2):492-8.
40. Ardlin BI. Transformation-toughened zirconia for dental inlays, crowns and bridges: chemical stability and effect of low-temperature aging on flexural strength and surface structure. *Dent Mater*. 2002;18(8):590-5.
41. Hallmann L, Mehl A, Ulmer P, et al. The influence of grain size on low-temperature degradation of dental zirconia. *J Biomed Mater Res Part B Appl Biomater* 2012;100(2):447-456.
42. Kohorst P, Borchers L, Strempel J, et al. Low-temperature degradation of different zirconia ceramics for dental applications. *Acta Biomater* 2012; 8(3):1213-20.

43. Ozer F, Mante FK, Chiche G, et al. A retrospective survey on long-term survival of posterior zirconia and porcelain-fused-to-metal crowns in private practice. *Quintessence Int.* 2014;45(1):31-8.
44. Cattani-Lorente M, Scherrer SS, Ammann P, et al. Low temperature degradation of a Y-TZP dental ceramic. *Acta Biomater.* 2011;7(2):858-65.
45. Kosmac T, Dakskobler A, Oblak C, et al. The strength and hydrothermal stability of Y-TZP ceramics for dental applications. *Int J Appl Ceram Technol.* 2007;4(2):164-74.
46. Tanaka K, Tamura J, Kawanabe K, et al. Phase stability after aging and its influence on pin-on-disk wear properties of Ce-TZP/ Al_2O_3 nanocomposite and conventional Y-TZP. *J Biomed Mater Res A.* 2003;67(1):2007.
47. Tsukuma K. Mechanical properties and thermal stability of CeO_2 containing tetragonal zirconia polycrystals. *Am Ceram Soc Bull.* 1986;65(10):1386-89.
48. Camposilvan E, Flamanta Q, Anglada M. Surface roughened zirconia: towards hydrothermal stability. *J Mech Behav Biomed.* 2015;47:95-106.
49. Zhang Y, Kim JW. Graded structures for damage resistant and aesthetic all-ceramic restorations. *Dent Mater.* 2009;25(6):781-90.
50. Zhang Y, Chai H, Lawn BR. Graded structures for all-ceramic restorations. *J Dent Res* 2010;89(4):417-21.
51. Garbelotto LGD, Maziero Volpato CA, Rocha M, et al. Laboratory and clinical considerations on prosthetic zirconia infrastructures for implants. *Implant Dent.* 2013;22(6):578-83.
52. Al-Haj Husain N, Özcan M. A study on topographical properties and surface wettability of monolithic zirconia after use of diverse polishing instruments with different surface coatings. *J. Prosthodont.* 2016 (Epub)